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This report presents a technical summary of the activities of the MURI during the period August 1996 through July 2001. To summarize, the main contributions of the MURI in this period have been to advance the basic state of knowledge in:

1. **Multi-modal control of "single agent" systems: modeling, analysis, control law synthesis and simulation**
2. **Design of hierarchical control architectures for multi-agent systems that share a single environment**
3. **Perception systems: (a) hierarchical aggregation (b) wide-area surveillance and (c) low-level perception**
4. **Frameworks for representing and reasoning with uncertainty**

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AN INTEGRATED APPROACH TO INTELLIGENT SYSTEMS

FINAL REPORT

S   SHANKAR SASTRY, ANIL NERODE AND ZOHAR MANNA

JANUARY 2002

ELECTRONICS RESEARCH LABORATORY
UNIVERSITY OF CALIFORNIA, BERKELEY

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AN INTEGRATED APPROACH TO INTELLIGENT SYSTEMS
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S. Shankar Sastry, Anil Nerode and Zohar Manna

1. Statement of the Problem Studied

This report presents a technical summary of the activities of the MURI during the period August 1996 through July 2001. To summarize, the main contributions of the MURI in this period have been to advance the basic state of knowledge in:
1. Multi-modal control of "single agent" systems: modeling, analysis, control law synthesis and simulation
2. Design of hierarchical control architectures for multi-agent systems that share a single environment
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4. Frameworks for representing and reasoning with uncertainty
5. Soft computing and evolutionary approaches to the design of complex systems

To our knowledge, we are the premier group in the country that has provided the analytic tools and frameworks for:
1. A theory of analysis, verification and synthesis of control laws for hybrid systems involving a combination of state-based continuous state dynamical models and IO-based concurrency models
2. Software tools for the simulation of hybrid multi-modal systems (SHIFT), the model-based verification and synthesis of hybrid control design (HyTech), and combined deductive-inductive verification tools (STeP)
3. Methods for the integration of multi-agent objectives into consistent, safe plans with performance metrics to quantify the emergent behavior
4. Fundamental new theory for the integration of control and sensory hierarchies (especially visual), with application to automatic driving and teleprescent environments
5. Novel methods for segmentation of images, implementation of low-level vision algorithms on neural network hardware, and the use of chaotic neural networks for representing complex patterns
6. Inference in dynamic probabilistic networks, first-order probabilistic modelling, multisensor monitoring of complex environments
7. Provably convergent algorithms for reinforcement learning
8. Model-based approaches to soft computing involving the simultaneous use of model-based approaches with fuzzy control, genetic algorithms

1.1. Collaborative Arrangements
The Center has developed collaborative arrangements with several other laboratories and other centers, such as:

- Yamaha Motor Co., Ltd. Aeronautic Operations, Shizuoka, Japan, autonomous flight

- Center for Autonomous Systems, Royal Institute of Technology, Stockholm, Sweden, in the areas of vision and control, multi-agent systems
- INRIA -CNRS VERIMAG, Grenoble, France, in the area of software tools for verification
- CNRS Robotics Laboratory, Toulouse, France, in the area of autonomous agents
- Control Laboratory, Lund, Sweden, in the area of software tools for the simulation of hybrid systems
- Honeywell Technology Center, Minneapolis, in the area of hybrid systems for flight management
- Magnetti Marelli, Rome, Italy, and Cadence Berkeley Labs in the area of hybrid control design tools for automotive control and CAD tools for verification
- University of Pennsylvania, mobile robots, visual servoing and verification
- NASA Ames Research Center, in the area of advanced air transportation technologies
- Laboratory for Computer Sciences, MIT, in the area of theory of distributed systems
- California PATH program on platooning and multi-agent collaboration
- Systems and Robotics Group, University of Porto, Portugal, in the area of coordination and control of multiple, autonomous, underwater vehicles
- NEXTOR, FAA Center of Excellence in Air Traffic Operations, at Berkeley, MIT, University of Maryland and VPI in the area of coordinated decision making and conflict resolution
- Intel Corporation and Xerox Corporation in the area of CAD tools for verification
- SRI in the area of verification tools
- Boeing, St. Louis in the area of Unmanned Aerial Vehicles
- Northrop Grumann, Los Angeles in the area of Unmanned Aerial Vehicles
- University of Southern California, Electrical Engineering, in the area of map building.

2.   Research Accomplishments

2.1   Distributed Multi-Agent Control Systems Architecture
Investigators: Shankar Sastry and Claire Tomlin

Claire Tomlin's group at Stanford University has been working on a mathematical model to represent and analyze numerous aircraft taking off ande landing simultaneously and designing a system in which conflict resolution for multi-aircraft scenarios is simplified through the use of flight modes, which are segments of constant heading, of constant bank angle, and of constant airspeed, familiar to pilots and easily implementable by autopilots. The problem of controlling an aircraft to such a trajectory plan is a hybrid one: it involves designing both the continuous control laws for the aircraft within each flight mode as well as the method for sequencing the discrete modes together. The construction of conflict resolution maneuvers as a sequence of discrete modes allows improvement in computational complexity over the full continuous trajectory planning algorithm, and more importantly, allows one to mathematically prove the safety of the maneuver for multiple aircraft conflicts. Her work on air traffic control automation involves conflict resolution of multiple aircraft in a free-flight scenario, where each aircraft follows trajectories that are mathematically guaranteed to avoid collisions with nearby aircraft. The take off and landing of multiple aircraft involves closely-spaced parallel approaches. Provably safe closely-spaced parallel approach maneuvers would ease the congestion of airports for which parallel runways are too closely spaced to

allow simultaneous landings under adverse weather conditions.

Tomlin's group has investigated hybrid dynamical systems with applications to air traffic management. Hybrid dynamical systems are continuous-time systems that have many different modes, or phases of operation. A switch from one mode to another may be triggered by an event that is either internal or external to the system. While the switches between modes have a defining logic and may be modeled by discrete-event systems, it has been shown that discrete-event or continuous-time tools alone are not adequate to model, analyze, or verify hybrid systems. The importance of a theory for hybrid control is its ability to provide a concise framework to analyze and design control algorithms and protocols for multi-agent, multi-objective systems. An excellent example of such a system is a partially automated air traffic management system. In such a system, much of the planning and control functionality for each aircraft is performed automatically by on-board avionics. However, the safety of such algorithms is currently "verified" by simulation for long periods of time with various initial conditions and inputs. She has proposed a method for designing hybrid control laws that can be used to guarantee safety of such systems. The method uses dynamic game theory, and generalizes a controller design method for purely discrete-event systems, and is used to design control laws for the automated resolution of trajectory conflicts between multiple aircraft, flight management system design, closely-spaced parallel approaches in automated air traffic control, and unmanned aerial vehicle design and control.

Shankar Sastry's group at Berkeley designed and fabricated autonomous unmanned aerial vehicles (helicopter-based robots) and unmanned ground vehicles (four wheel drive, differential skid-steering all-terrain robots) capable of supporting research on a number of topics, including multi-agent hybrid systems involving sensor fusion, coordinated mission planning and distributed control. The unmanned aerial vehicles (UAVs) are responsive to requests for basic flight maneuvers such as takeoff, landing, hover and waypoint navigation. Each UAV consists of a base airframe and integrated avionics systems, that includes path planning, flight control system, navigation sensors and a communication module. A team of unmanned ground vehicles (UGVs) are equipped for similar research operations, with a base all-terrain vehicle and navigation system which decomposes a mission into self-localization or position estimation waypoinhts based on a combination of dead reckoning with periodic compensation using external navigation data. GPS is the primary navigation sensor. Other components for sensing and navigation include cameras, position encoders, digital compasses and range-finding ultrasonic sonar transducers. The autonomous vehicles exchange data over a wireless network. The UAV/UGV system is inherently hybrid, having to combine continuous control with discrete logic. Hierarchy makes it possible to separate complex global tasks into a series of simpler, local ones. The strategy planning and probabilistic map building of the environment is done either on board each vehicle or at a base station, depending on the degree of information centralization.

To validate the proposed architecture, pursuit-evasion game scenarios have been enacted in which a group of pursuers are attempting to capture another group of evaders within a fixed and unknown arena that may contain fixed obstacles. A hierarchical architecture was developed for coordination and control of autonomous agents performing intelligent team operations. Blue and red teams, consisting of multiple aerial and ground vehicles coordinate strategy through communication via a wireless network. Intelligent multi-agent systems address optimization, coordination, fault detection-tolerance, stability, with reduced control and cognition complexity, adaptivity to changes in task and environment, modularity and scalability to perform complex missions.

ARO MURI papers 2000-2001

A Game Theoretic Approach to Controller Design for Hybrid Systems. Claire Tomlin, John Lygeros and Shankar Sastry. Proceedings of the IEEE, vol 88, no. 7, 949-969, 2000.

Hierarchically Consistent Control Systems. George Pappas, Gerardo Lafferriere and Shankar Sastry. IEEE Transactions on Automatic Control, vol 45, no. 6, 1144-1160, 2000.

Control System Design for Rotorcraft-based Unmanned Aerial Vehicles Using Tiome-domain System Identification, David Shim, H. Jin Kim and Shankar Sastry. IEEE Intl Conference on Control Applications, Anchorage, 2000

A Flight Control System for Aerial Robots: Algorithms and Experiments, H. J. Kim, D. H. Shim, and S. Sastry. 15th IFAC World Congress on Automatic Control, Barcelona, Spain, July, 2002. (accepted for publication)

A Flight Management System for Unmanned Aerial Vehicles with Nonlinear Model Predictive Tracking Control, H. J. Kim, D. H. Shim, and S. Sastry. ACC, Anchorage, AL, May, 2002 (accepted for publication).

FLYING ROBOTS: Sensing, Control and Decision Making, H. J. Kim, D. H. Shim, and S. Sastry. IEEE International Conference on Robotics and Automation, Washington, DC, May, 2002. (accepted for publication)

A Hierarchical Approach to Probabilistic Pursuit-Evasion Games with Unmanned Ground and Aerial Vehicles, H. J. Kim, R. Vidal, D. H. Shim, O. Shakernia, and S. Sastry. IEEE Conference on Decision and Control, Orlando, FL, December, 2001.

2.2   Hierarchical Sensing and Control
Investigators: Jitendra Malik and Shankar Sastry

Capability of reasoning in terms of objects and their behaviors is crucial for mid and higher level control. This requires that we be able to group the spatiotemporal information into separate objects.

Jitendra Malik's group developed a novel framework for grouping known as Normalized Cuts. The image is considered to be a weighted graph where the nodes are pixels and arcs weights denote a local measure of similarity between the two pixels. Grouping can then be performed by finding eigenvectors of the Normalized Laplacian of this graph. Brightness, color, texture, motion similarity, proximity and good continuation can all be encoded into this framework. We also came up with a solution to the problem of cue integration for image segmentation.

Identifying particular combinations of regions as being instances of known objects. We introduced a new shape descriptor, the shape context, for correspondence recovery and shape-based object recognition. The shape context at a point captures the distribution over relative positions of other shape points and thus summarizes global shape in a rich, local descriptor. We use the shape context as a vector-valued attribute in a bipartite graph matching framework. Our method makes use of a relatively small

number of sample points selected from the set of detected edges; no special landmarks or keypoints are necessary. Tolerance and/or invariance to common image transformations are available within our framework.

Shape contexts greatly simplify recovery of correspondences between points of two given shapes. Moreover, the shape context leads to a robust score for measuring shape similarity, once shapes are aligned. It is thus a generic method with applications in object recognition, image registration and point set matching. Using examples involving both handwritten digits and 3D objects, we illustrated its power for object recognition.

The other main focus of our research effort was in developing a deeper understanding of multiview geometry, as applicable to the recovery of structure from motion. Multiview geometry conceptually, can be viewed as a geometry which studies the combination of any motion group (acting on certain spaces) and a perspective projection (properly interpreted in respective spaces). In the default case, the motion group is the special Euclidean group acting on the three-dimensional Euclidean space, and the perspective projection is simply the standard one. In the same spirit, we should be able to study vision under any motion groups. The traditional projective geometry based approach can then be interpreted as arising when the special Euclidean group is substituted by the general linear group for simplification. Respectively, the underlying space becomes a projective space rather than the Euclidean one. To take this one step further, if the motion group is replaced by some other ones, the underlying spaces can even be any non-Euclidean spaces.

We have unified our results and understanding in multiview geometry in a framework which we call "a differential geometric approach''. The conceptual interpretation of multiview geometry above is by no means the only reason for us to adopt differential geometry. Our work has shown that differential geometry serves well as a framework which provides us geometric intuition, interpretation and tools to almost every problem that we have studied about multiview geometry, for example:

- The unification of discrete and continuous linear algorithms relies on a clean geometric characterization of the space of essential and continuous essential matrices.
- The nonlinear algorithms for obtaining optimal (or suboptimal) estimates rely on modern optimization techniques for special classes of Riemannian manifolds.
- The proof of geometric dependency of constraints among multiple images relies on a clever trick on a quotient space of a Grassmann manifold.
- The discovery of degeneracy of Kruppa's equation relies on a new interpretation of Kruppa's equation as inner product invariants of certain isometry group action.
- A classification of generic ambiguities in the problem of 2D to 3D reconstruction is done with respect to every Lie subgroup of the special Euclidean group.

Another obvious reason is that differential geometry has already been widely adopted in the study of linear/nonlinear systems and modern robotics. A theory of multiview geometry based on such a language will certainly be more accessible to people in these communities. It may provide a more unified framework for the study of vision-based control or vision in presence of multiple kinematic chains.

Over the past years of the MURI Shankar Sastry's group has performed numerous computer vision experiments in robotics and control applications for autonomous navigation, obstacle avoidance, object recognition and manipulation, 3D map building. In all these areas an important question is how to recover geometric and dynamic information from the scene being observed.

One of the experiments using the Berkeley robotic helicopters is the landing of an

autonomous unmanned aerial vehicle using computer vision as a feedback sensor in a control loop. The vision problem addressed in this autonomous landing experiment is a special case of the classic ego-motion estimation problem since all feature points lie on a planar surface (the landing platform). The group studied together the discrete and differential versions of the ego-motion estimation, in order to obtain both position and velocity of the unmanned aerial vehicle relative to the landing platform, developed a unified geometric framework and a new estimation scheme for solving the differential case, showing how the obtained algorithms enable the vision sensor to be placed in the feedback loop as a state observer for landing control. These algorithms are linear, numerically robust, and computationally inexpensive hence suitable for real-time implementation. The results of landing experiments present a thorough performance evaluation of the motion estimation algorithms under varying levels of image measurement noise, altitudes of cameras above the landing platform, and different camera motions relative to the landing platform

Sastry's group also studied the classic problem in computer vision, "the structure from motion problem" as a constrained nonlinear least squares problem which minimizes the so-called reprojection error subject to all constraints among multiple images. By converting this constrained optimization problem to an unconstrained one, multilinear constraints, when used for motion and structure estimation need to be properly normalized, which makes them no longer tensor constraints. It was demonstrated by using bilinear epipolar constraints and shown how they give rise to a multiview version of the (crossed) normalized epipolar-constraint of two views. Such a (crossed normalized epipolar constraint serves as an optimal objective function for motion (and structure) estimation. This objective function further reveals certain non-trivial relationships between geometric and algebraic dependency among multilinear constraints, that is, even rectilinear motion can be correctly estimated by normalized epipolar constraint only, hence trifocal tensors are not really necessary. The proposed algorithm was demonstrated in simulation and experiments.

ARO MURI papers 2000-2001

Landing an Unmanned Air Vehicle: Vision Based Motion Estimation and Nonlinear Control, Omid Shakernia, Yi Ma, John Koo and Shankar Sastry. Asian Journal of Control, vol 1, no 3, 128-145, 1999.

Optimal Motion Estimation from Multiple Images by Normalized Epipolar Constraint, Y. Ma, R. Vidal, S. Hsu and S. Sastry. Communication in Information and Systems, vol 1, no. 1, pp 51-75, 2001.

Optimization Criteria and Geometric Algorithms for Motion and Structure Estimation, Yi Ma, Jana Kosecka and Shankar Sastry. International Journal of Computer Vision, vol 44, no 3, 219-249, 2001.

Linear Differential Algorithm for Motion Recovery: A Geometric Approach, Y. Ma, J, Kosecka, S. Sastry. International Journal of Computer Vision, vol 36, no 1, 71-89, 2000.

2.3   Specification and Verification of Multi-Agent Hybrid Systems
Investigator: Zohar Manna

Since 1994, Manna's group has been developing STeP, the Stanford Temporal

Prover, an integrated toolset that supports the computer-aided formal verification of reactive systems based on temporal specifications. STeP combines model checking with deductive methods to allow the verification of a broad class of systems, including parameterized (N-component, for arbitrary N) systems, and systems with infinite data domains. Under the MURI project STeP has been extended to support the deductive verification of hybrid systems, and to our knowledge, it is the first dedicated verification system with built-in support for the deductive verification of such systems.

STeP has been extended with modular and abstraction-based techniques for the study of hybrid and real-time systems, including the diagram-based techniques that have proved effective for the verification of reactive systems. In the past funding year, a large part of STeP has been reimplemented in Java, with the objective to create a more open architecture that allows integration of tools for symbolic and numerical math, which are necessary tools for analyzing non-trivial hybrid systems.

To model hybrid systems, we use phase transition systems, which contain both discrete transitions and continuous activities that describe the evolution of continuous variables, using differential equations and or differential inclusions. Temporal properties of hybrid systems are verified by verification rules and verification diagrams. Verification rules are used to reduce temporal properties of systems to first-order verification conditions. Verification diagrams provide a visual language for guiding, organizing and displaying proofs. Verification diagrams have been extended to support modular reasoning and to prove nonzenoness and receptiveness. A diagram is constructed to analyze the behavior of each system module; the diagrams for the different modules can then be automatically combined into the correctness proof for the global system. In addition, techniques for automatic invariant generation of hybrid system have been developed.

These techniques can be used to aid with the generation of the appropriate verification diagrams; in some cases, the techniques are sufficiently powerful to lead to the automatic proof of the specification. To aid with the analysis of verification diagrams, and in particular with the discharge of the verification conditions associated with the diagrams, we have developed a general framework for combining decision procedures. This framework enables to harness the power of independently-developed procedures towards the joint goal of proving the validity of verification conditions. This results in a modular, expandable architecture of the theorem prover used for deductive verification, which enabled the verification of complex systems with a minimum of user intervention. The following were the project headings supported by the MURI:

- Verification of performance and reliability of real-time systems
- Game-based specification and verification techniques for multi-agent systems
- Visual, deductive methods for the modular verification of hybrid systems
- Use of deductive techniques jointly with model checking
- Logics and automata-based methods for the specification and verification of real-time and hybrid systems

2.4. Architectures for Multi-Agent Hybrid Systems
Investigator: Anil Nerode

Nerode's group has constructed a natural common semantics which meets stability requirements not naturally guaranteed by correctness in existing languages, and is explained in terms of the Kohn-Nerode methodology. The goal of the Kohn-Nerode hybrid distributed autonomous control architecture is to establish the mathematics and computer science of extracting and checking correctness of digital control programs

which claim to enforce performance specifications for such systems. We regard as a key issue assuring that an extracted control program still meets the program specification even if the parameters of the plants controlled and the communication links are not exactly what we think they are; and that we should be able to compute how much error in parameters still keeps us within the program specification. This is a weak necessary condition form of stability. We believe that this has to be part of correctness, needed to write adequate design requirements for sensors, effectors, communication lines, and plant.

If, as many workers have, one turns the whole hybrid system into an automaton by digitizing sensor, effector, plant, and communication line states, and then extracts a digital control program by automata theory, one has no assurance that with small changes in the parameters of the system the program will still meet performance specifications. The same thing often happens if one simply writes every event driven decision in an event driven language as if every value is perfectly known. Further, when one composes get estimates in general for the tolerable error of the composition from that for the parts. If one treats this directly as a numerical analysis problem without discretizing, there is no high-level language expressing this. Many performance specifications have nested quantifier specifications. These arise with liveness and termination, and whenever one sort of firing of an event always or never causes another, etc. Stability under small changes of parameters should be proved for these nested statements as well.

We believe we have a satisfactory answer with new semantics tuned to hybrid systems such that programs correct with respect to this semantics have the kind of stability referred to above. This is a new semantics for *all* the languages for hybrid systems. This common semantics for all hybrid languages will allow them to be "mixed and matched". Programs in each language correct in this new semantics can be readily composed, so that calling subroutines compiled in one language into another is just fine. The crudest form of the semantics keeps track of tolerance to errors. They are not named in the language itself. We confine ourselves to describing this semantics.

Hybrid control programs that have been declared correct by current language semantics of current hybrid languages may not be correct in the new semantics. With some exceptions such as some of Nancy Lynch's work, or piecewise linear plants, they usually have to be reworked using mathematical analysis and rewritten to get programs correct in the new semantics. For the new semantics declares that those programs that cease to obey the performance specification for arbitrarily small changes in some physical parameters are *incorrect*. This semantics sharpens present correctness notions for hybrid systems to give a more engineeringly meaningful notion where correctness involves the analysis of behavior of the differential or variational or other equations obeyed by the physical plants being controlled. We have believe that appropriate Kohn-Nerode algorithms for extracting control programs are correct in the new semantics, assuring the form of stability mentioned above. All computer language semantics can be viewed as Scott semantics on an appropriate CPO, just as all mathematics can be viewed as category theory on an appropriate category. That is true here, but as an insight it does not give value; that is, there are no deep theorems to apply.

We explain briefly the new semantics, using Prolog as a control program language. We omit other languages because they take some effort to explain. In the Kohn-Nerode setup a Prolog program is the control program; the input state of the plant fires an atomic statement. The Prolog program computes and terminates. The answer substitution gives the next control law to use. The requirement that an arbitrarily close plant states fire the same input letter plus the finiteness of the input alphabet says that the topology generated by the open sets that fires the input letters is a finite distributive

lattice of sets. It generates a finite Boolean algebra. The atoms are a partition of the plant sets. The control automaton cannot distinguish between plant states if they are in the same partition set.

We take it that there are two topologies involved on the plant state space: the usual plant state topology, and the finite topology just mentioned, which is a finite topology representing what the control program can distinguish about the plant states through the sensors. It is natural to say that each Prolog atomic statement *denotes* the open set of plant states that fire it. This open set is a subset of the original plant state space with its original topology and is also in the plant state space small topology. We now apply the Tarski-Rasiowa-Sikorski topological semantics for predicate logic of which Prolog is a part; negation is omitted because it is definable from implication and falsity. Every atomic statement has been assigned a denotation which is an open set in the plant topological space. Define by induction on the length of formulas the denotation of every statement: "and" goes to intersection, "or" to union, "A implies B" to largest open set containing A and disjoint from B, "T" to the whole space, "F" to the empty open set, existential quantifier to the union over instances, universal quantifier to the interior of intersection of instances. In case there are constants naming every partition set and the predicates are about these partition sets, as is the case with our Prolog programs, the universal quantifier reduces to a finite union, and we are dealing with a finite model whose domain consists of the partition sets. A correct statement is one denoting the whole space. Correctness in our sense refers to a specification being satisfied by the Prolog program in the sense of this topology. The statements valid in all such topological models, as the topological space varies, Rasiowa-Sikorski proved are those that are intuitionistically valid. This implies that the rules of inference to be used are the intuitionistic ones only, and that we are talking about intuitionistic validity in a finite model associated with a finite topology when we prove the correctness in our sense of a Prolog program. Programs with input and output letters should be composed so that if an output atomic statement is the input to another such program, the open set denoting the output atomic statement should be a subset of the open set denoting the input atomic statement.

This gives a hint as to how the same ideas will apply to all other proposed formalisms. We are suggesting that only intuitionistically correct deductions be used (as in Prolog), and that specifications are read the the same way, and can be in full intuitionistic logic.   We do not have space to explain why this interpretation guarantees stability in the sense we mentioned of performance specifications with alternating quantifiers in their statement, but it does.   We cannot go further here.

Nerode's work on hybrid systems theory and applications was devoted to further development of the Kohn-Nerode theory of multi-agent hybrid control systems based on the calculus of variations, automata theory, and differential geometry as a basis for intelligent systems. The aim of this theory is to find algorithms for extracting digital control programs from performance specifications and simulation models for complex interacting heterogeneous systems, or hybrid systems. Such a system consists of both continuous plants and digital programs. In a large military problem, the plants may be military assets such as tanks and planes, the digital programs may be AI command and control assistants, the simulation models may be for distributed simulation. At a more pedestrian level, the plants may be power stations and power users, the digital programs may be those that route power through distribution centers. Synchronization of multimedia applications. Distributed simulation problems are of the same genre.

Nerode also explored non-monotone logics for AI and hybrid systems which involved an exploration of logics and algorithms for intelligent systems which deal with how to change "belief systems" when facts intervene to show that the beliefs cannot be

valid and must be replaced by new "belief systems". Suppose that a system under digital control is observed to fail to meet its performance specification, which it would meet if the model of the system used in designing the control system was correct. How does one revise the model using this new information, and derive a new control system controlling the new structurally changed model? This is within the area of non-monotonic reasoning. A typical military problem of this type is how to replan, redeploy, reallocate resources as friendly assets are destroyed and unexpected new enemy assets arrive in the field. Also of this genre is making sure that when part of a complex system under control fails, that the control is changed to fit what is known about the structural model of what is left. Power system failures due to storms, or due to failures of large generators, are of this type. Algorithm development in this area is very taxing.

Jennifer Davoren, a postdoctoral researcher in Nerode's group. formulated and justified the view that the modal mu calculus, among all current formal systems, is best suited to model and verify hybrid systems. She showed by example that its natural proof procedures correspond very closely to those used in informal verification, a substantial advantage over temporal logic formulations. She investigated hybrid systems as heterogenous dynamical systems characterized by interacting continuous and discrete dynamics. The high-profile and safety-critical nature of the application areas, such as air traffic control and automated manufacturing and chemical process control, has fostered a large and growing body of work on formal methods for hybrid systems: mathematical logics, computational models and methods, and computer-aided reasoning tools supporting the formal specification and verification of performance requirements for hybrid systems, and the design and synthesis of control programs for hybrid systems that are provably correct with respect to formal specifications. Their work on the MURI program continues to provide original contributions to the use of logics and formal methods in the analysis of hybrid systems, specifically in the area of hybrid controller synthesis problems. Recent work formulates and robustly solved a quite general class of hybrid controller synthesis problems, focusing on the switching control mechanism of a hybrid automaton (via guard and mode invariant sets). The robustness result is with respect to variations in the right hand sides of the differential equations that depend continuously on a parameter. We present a novel methodology for controller design and synthesis which uses modal logic as a formalism for reasoning about sets of plant states, and various operators on sets arising from the differential equations and from metric tolerance relations on the state space.

2.5.   Intelligent Agents for Complex, Uncertain Environments
Investigators: Stuart Russell and Daphne Koller

Russell's group advanced the state of the art by developing new methods for learning in the presence of incomplete data (e.g., data with missing values and hidden unobservable variables)--major computational overhead in learning.   To facilitate learning in complex domains, inference algorithms that are especially tuned for the learning task A novel algorithm for probabilistic matching was developed and applied it for matching vehicles in image sequences from traffic surveillance cameras that view different segments of the same highway. New hierarchical decomposition techniques were developed that allow to perform decision-theoretic planning and reinforcement learning in large domains that cannot be handled by standard methods.

Koller's group made progress in devising frameworks that support the hierarchical decomposition of complex stochastic systems into multiple interacting processes. These include a stochastic extension of interacting finite automata for

representing stochastic processes and a stochastic extension to a functional programming language for representing distributions over regular structures such as parse trees These works lay the foundations for combining methods from the probabilistic network literature to hybrid systems. In another line of research, Koller's group made interesting progress in its work on learning, inference, and planning. Focus was on learning Bayesian networks, intelligent decision modeling, and on planning in Markov decision processes (MDPs), specifically, the modeling of decision behavior. This task is fundamental to many applications at the forefront of AI, for example, in the design of multi-agent systems or for human-computer interaction. Its solution entails representing an agent's behavior in terms of a suitable class of utility functions and identifying a concrete element of this class using one of various techniques. In particular, the group explored an approach where the utilities can be viewed as random variables whose density can be estimated using historical interactions. This density can be used as a prior, which is then conditioned based on observations of the agent's behavior. The group developed an algorithm for performing utility elicitation in a way that reveals the agent's utility function using a small number of elicitation questions.

A topic that is closely related to utility solicitation is the identification of optimal decision rules based on the agent's utility function. This objective becomes particularly challenging if there are dynamic interdependencies between the decisions at different points in time. This situation can be modeled using the MDP framework. The group's work led to several new advances in this area. In particular, it extended its vision of simplifying probabilistic computations by exploiting problem structure. A key development was a new algorithm that approximates the solution to a complex factored MDP using approximate policy iteration. This algorithm leads to exponential computational savings by comparison to the exact solution of the factored MDP.

An ongoing theme of the group's work is the learning and inference in Bayesian networks. The members of the group have focused on several aspects: First, they investigated algorithms to learn model structure in a Bayesian framework. Second, they extended their existing work for parameter estimation in Bayesian networks to include "active learning". Active learning is crucial in scenarios where we can choose between different data items for learning at each time step. It is particularly important in cases where obtaining data is particularly expensive. Active learning of model structure is a completely novel approach that was found to be extremely useful for dealing with very large data sets.

A special class of Bayesian networks that is suited for many real problems are Dynamic Bayesian Networks (DBNs). DBNs have been promoted as a powerful framework for the modeling of dynamic systems in earlier work, with a focus on efficient algorithms to exploit problem structure. In the reporting period the group extended this theoretical framework so as to allow also for the modeling of fault detection and diagnosis in dynamic systems. An important aspect of this work is that it focuses on DBNs which may contain both discrete and continuous random nodes. The modeling of these hybrid systems is computationally particularly challenging. At the same time the solution of this problem is particularly important because most real-world systems are hybrid by nature. The newly algorithm lead to drastic performance improvements in various example problems.

The extraction of single features that serve to approximate the state of the system in a compact manner. While feature selection is a relatively standard approach to deal with pattern recognition tasks, it has been used essentially as a heuristic in the context of MDPs. In this new work the group established for the first time a direct formal link between the performance loss due to the approximation and the information about the system state contained in the features. Initial experiments demonstrate that a very

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small number of features can be sufficient to approximate the exact solution of an MDP well. This direction of research may lead to a breakthrough in the practical applicability of Markov Decision Problems and Partially Observable Markov Decision Problems

Jordan's group developed a methodology for approximate probabilistic inference known as "variational inference." The basic idea is that the symbolic complexity inherent in expanding sums of products in probabilistic computations is not necessarily reflective of the numerical complexity of the final result. In particular, laws of large numbers come to the rescue, and many sums do not need to be performed explicitly because their result is predictable. The goal of their work was to design algorithms that exploit this idea in the graphical models setting. They developed a number of such algorithms, using ideas from statistical physics, convex analysis and large deviation theory. The result was a suite of deterministic algorithms that provide anytime bounds on marginal and conditional probabilities of interest.

Jordan's group developed a variational inference algorithm for diagnosis in a large-scale graphical model. This model---the QMR-DT medical database---involves approximately 5000 nodes and is one of the largest probabilistic databases in existence. The variational algorithm provides accurate estimates of diagnostic probabilities for QMR-DT in under a second of computer time. By way of comparison, it is estimated that exact probablistic inference algorithms for QMR-DT would require 50 years to run. It is also known that sampling algorithms (Markov chain Monte Carlo algorithms) are slow and give unreliable results for QMR-DT.

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2.6 Soft Computing and Neural Networks
Investigators: Walter J. Freeman and Lotfi A. Zadeh

Walter Freeman's MURI research was devoted to measurement and description of electroencephalographic (EEG) and unit activity of cortex that occurs during goal-directed behavior. Behaviorally relevant information is carried by spatial patterns of amplitude modulation of gamma waves (20-80 Hz in rabbits, 35-60 Hz in cats), which are triggered in the cortex by input from receptors and relays in frames at theta frequencies (2-7 Hz). Behavioral testing has shown that amplitude patterns of gamma activity are invariant with respect to learned odor stimuli, but change with context and reinforcement under conditioning. The same algorithms hold for olfactory, visual, auditory and somatic cortexes. These spatial patterns are shaped by inputs from the limbic system in the form of corollary discharges, as the basis for attention and expectancy, and by the history of experience with stimuli that is embedded in the cortical neuropil by synaptic modifications due to learning. The patterns manifest not the features of stimuli, but the meaning of the stimuli for the animals. Freeman has modeled the dynamics of the cortex by networks of nonlinear differential equations. The solutions to these equations show the existence of equilibrium, limit cycle and chaotic attractors, which we display with interactive graphics. The model performs with outstanding efficacy the basic functions of sensory cortex: abstraction, generalization, and classification.

Existing methods of complexity research are capable of describing certain specifics of biosystems over a given narrow range of parameters. In his MURI project a new approach to chaos research was used that has the potential of characterizing biological complexity. This study is biologically motivated and solidly based in the biodynamics of higher brain function. At the same time it outlines a deep mathematical analysis into the foundations of chaos theory and dynamical systems. Freeman's biocomplexity model has the following features:

- It is high-dimensional, but the dimensionality is not rigid, rather it changes dynamically;
- It is not autonomous and continuously interacts with and communicates with individual environments that are selected by the model from the infinitely complex world; as a result, it is adaptive and modifies its internal organization in response to environmental factors by changing them to meet its own goals;
- It is a distributed object that evolves both in space and time toward goals that it is continually re-shaping in the light of cumulative experience stored in memory;
- It is driven and stabilized by noise of internal origin through self-organizing dynamics.

Of special interest are input-induced and noise-generated, or spontaneous state-transitions and the stability properties of the emergent systems over certain spatial and

temporal scales. Adaptation and learning are key components of our model. He applied his new mathematical tools for industrial and biological information processing to data sets from our laboratory, using landscapes of chaotic attractors. The sensitivity to initial conditions might seem to hold promise for signal detection, owing to an implied capacity for distinguishing small differences in patterns. However, this sensitivity is incompatible with pattern classification, because it amplifies irrelevant differences in incomplete patterns belonging to the same class, and it renders the network easily corrupted by noise. We developed a theory of stochastic chaos, in which aperiodic outputs with I/f2 spectra are formed by the interaction of globally connected nodes that individually are governed by point attractors under perturbation by continuous white noise. The interaction leads to a high-dimensional global chaotic network that is stabilized by additive noise modeled on biological noise sources. Systematic parameterization of the interaction strengths corresponding to synaptic gains around nodes representing excitatory and inhibitory neuron populations enabled the formation of a robust chaotic attractor landscape. Reinforcement learning from examples of patterns to be classified using habituation, association and re-normalization creates lower dimensional local basins in the global attractor landscape with one basin for each class. Thereafter, presentation of incomplete examples of a test pattern leads to confinement of the KIII network in the basin corresponding to that pattern, which constitutes many-to-one generalization. The capture after learning is expressed by a stereotypic spatial pattern of amplitude modulation of a chaotic carrier wave. Sensitivity to initial conditions is not longer an issue. Scaling of the additive noise as a parameter optimizes the classification of data sets in a manner that is comparable to stochastic resonance. The local basins constitute dynamical memories that solve difficult problems in classifying data sets that are not linearly separable. New local basins can be added quickly from very few examples without loss of existing basins. The attractor landscape enables the KIII set to provide an interface between noisy unconstrained environments and conventional pattern classifiers. Examples were shown of its robust performance, including fault detection in small machine parts and the classification of spatiotemporal EEG patterns from rabbits trained to discriminate olfactory stimuli.

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**3.	Experimental Testbeds**

**3.1	Berkeley Aerobot Project: Vision-based Navigation System**

Implementation and Results. The following equipment is integrated on our Yamaha R-50 based unmanned helicopters. A similar setup is used for the Pioneer all-terrain ground robots.

Navigation computer:
Pentium 233MHz Ampro Littleboard running QNX real-time O-responsible for low level flight control
NovAtel MillenRT2 GPS system, 2cm accuracy
Boeing DQI-NP INS/GPS integration system

Vision computer:
Pentium 233MHz Ampro Littleboard running Linux OS-responsible for vision algorithms and camera control
Sony EVI-D30 Pan/Tilt/Zoom (PTZ) camera
Imagenation PXC200 framegrabber
2 SanDisk 220MB PCMCIA hard disks
Lucent Technologies' WaveLAN wireless ethernet card for each computer

Our vision computer communicates with the navigation computer over a 115200 bps RS232 serial link. Currently, we only use that link to gather INS/GPS state information from the navigation system for comparison with the vision-based state estimates. We communicate with the PTZ camera over a 9600 bps RS232 serial link to send pan-tilt commands and receive the current pan-tilt state. We capture grayscale images from the PXC200 at a resolution of 320x240 pixels at 30 frames per second asynchronous to program execution through memory-mapped IO and system signals. To reduce the cost of thresholding, we estimate the image histogram by considering one-seventh of the total image pixels. Furthermore, we use a multi-resolution approach in our segmentation algorithm to improve processing time, effectively performing segmentation on a 160x120 image. We then calculate the edges of the interior squares of the landing target from the original 320x240 image. We develop and debug our vision algorithms using MATLAB then translate them by hand to C++ for execution on the vision computer. LAPACK (Linear Algebra PACKage) and BLAS (Basic Linear Algebra Subprograms) are used for matrix operations such as multiplication, SVD, eigenvalue decomposition, and Gaussian elimination. Our remaining code uses a flexible object-oriented program structure written in C++. In particular, we developed a class specifically for communicating with the Sony PTZ camera. We also wrote abstract communication classes to allow for transparent communication through TCP/IP sockets, serial IO, file IO, or standard IO. We found this level of IO abstraction reduced costs in developing communication layers with the navigation computer and ground station.

Our ground station displays the current state of the vision system through a Java-based GUI. In addition to the current vision-based state estimates, we bit-pack the thresholded 160x120 binary image for display on the ground station. We find that this real-time view from the PTZ camera is invaluable for testing by not only giving feedback regarding the state of the helicopter, but by also showing the quality of thresholding

algorithm and the pan/tilt control. In practice, we find that while the pan/tilt control performs as well as can be expected, there is still room for improvement in our selection of the threshold. We also display the current labeled feature point estimates to gauge the quality of the corner detection and labeling algorithms. In practice, we find that while our corner detection algorithm produces somewhat noisy estimates, our corner labeling algorithm is extremely robust.

Flight Test Results. For the flight test, we saved every fifth grayscale image for data logging. As it turns out, the Linux (kernel 2.2.12) write caching system is less than optimal for this type of load. As a result, the system averaged a 1.2 second suspension of all processing every 10 seconds while the write cache was flushed. Naturally, this delay is also a function of the PCMCIA hard disk used for storing the image sequence. However, in a real flight, the operating system would not have the burden of logging this data, and a consistent 30 frames per second is otherwise sustainable.

Figure 7 shows the results of our flight test with the UAV, comparing the output of the vision-based state estimation algorithm with the INS/GPS measurements accurate to 2 cm. All plots show the state of the RUAV with respect to the landing pad. The vision estimates are more noisy, but otherwise follow the INS/GPS measurements. Also, errors in the internal and external camera calibration parameters marginally affect some of the estimates-the x-position and z-rotation, in particular. The delay caused by the Linux write caching algorithm is noticeable by the synchronized gaps in data in each plot.Overall, the vision-based state estimates are accurate enough to be used in a high-level controller for landing in a hierarchical flight vehicle management system.

3.2   Berkeley Telesurgical Workstation

The telesurgical workstation testbed project had a dual focus. One focus has been the testing and evaluation of the bimanual system by surgeons at UCSF. The other focus has been continued development on the unimanual system. Some of the project's accomplishments:

Results from Tests at UCSF Medical Center

UCSF Medical Center surgeons evaluated the bimanual robot. UCSF Medical Center surgeons have now completed a round of evaluation on the bimanual surgical robot system. This evaluation has included both formal testing, such as timed trials, and informal feedback as well (e.g. see next item).

Evaluated modified gripper shape. We reported last year that our existing needle gripper (left frame below) was best for many minimally invasive tasks, and that we would soon evaluate a gripper with curved jaws (right frame) for other tasks. However, in the evaluation by UCSF Medical Center surgeons, we found the new jaws to be so effective that there was no longer any need for the older straight ones. UCSF surgeons found the new jaws' curvature, rounded edges, and added length enhanced their ability to suture and to tie knots with the robot.

Counterbalanced the surgeon's control sticks. To reduce fatigue and enhance the surgeons' dexterity with the robot, the bimanual system's master control station was upgraded to include active counterbalancing of the control sticks. Although there is still no force fed back from the surgery site itself, at least the distracting weight of the control sticks has been eliminated, allowing more of the surgeon's attention to be focused on the feedback available visually. Besides comfort, dexterity, and reduced fatigue, an added advantage of the counterbalancing is that now the control sticks not stay put

where the surgeon lets go of them.

This counterbalancing has been achieved using the motors in the Phantom designed for force feedback. This continuous force application by the motors sometimes overheats them, requiring shutdown of the system. We plan to alleviate this by adding a metal counterweight. This will reduce the required motor torque by a third or more, eliminating the threat of overheating.

Software/Hardware Implementations

Software development specified for the redundant encoders. Background: Each robot arm incorporates a gross position stage driven by three linear actuators. Each linear actuator has an encoder to permit closed loop control. In order to prevent the encoders on the linear actuators from acting as single points of failure, we have added redundant encoders. Furthermore, we have located these new encoders where they monitor the gross stage's 3 degrees of freedom in a different way from the original encoders on the 3 linear actuators. By doing this, they not only verify the readings of the original encoders, they simultaneously monitor themselves and the validity of their associated kinematics calculations. However, these calculations require iterative solving of non-linear equations. The software challenge has been to fit iterative calculation into a real-time context.

This software development plan for the redundant encoders will unfold in three stages. The first stage, already complete, is a thorough mechanical survey of each robot arm.

The second stage, about to begin, is a detailed walk through of the existing kinematics software (using the original encoders). Quantitative comparisons will be made between values in the code and those found in the survey. As a checksum on these individual comparisons, each robot arm will be operated with special attention paid to the exact position it achieves as compared to its commanded position. To do this check properly, we will need to replace the current, approximate, reverse (and forward) kinematics with the exact solutions. However, we will not yet have a satisfactory way to calculate one of these (the forward kinematics) in real-time. (It will be developed in stage three.) However, once teleoperation is running, we need only the inverse kinematics. Thus, we will begin teleoperation with the existing approximate kinematics, and then shift-on-the-fly into exact kinematics. Observing the millimeter-scale movements prompted by said shifting ought to be insightful as well, telling us much about the magnitude and spatial shape of the difference between our exact and approximate solutions.

Up to now these millimeter-size systematic (or smoothly varying) deviations have not affected the robot's performance. However, to utilize redundant encoders they must be tracked down.

The third stage will be to choose a method of performing exact forward kinematics in real-time. While not strictly necessary during teleoperation, it will be needed in order to utilize the redundant encoders. It will also be needed to smoothly transition into holding before teleoperation. This choice will be informed by observations made during stage two. Most likely we will choose Newton's method. A special modification may be needed for the case of transitioning from idle mode to holding or teleoperate mode. In this special case, the Newton's method routine might be given the power to hold of transition of the state machine out of idle until it converges on a solution. Once the robot is teleoperating, the previous position ought to provide an excellent starting point, permitting Newton's method to converge in 1 to 2 iterations.

Modify the robot software to improve motor coordination. The robot software

has been modified to produce smoother motion without requiring any increase in data bandwidth between the surgeon's control station and the robot. This has been accomplished by computing an interpolated path between successive position and orientation coordinate sets sent by the surgeon's control sticks to the robot.

Last year we stated an intention to also handle for the possibility of an obstruction in the robot's path by ensuring that it follows a computed path. This was intended to avoid going too far off of a straight-line path from one 6 D.O.F. coordinate to the next. This concern has turned out to be an artifact of the (no longer used) kinematics software's singularity. Current software never attempts to drive the robot a large distance in a single time-step. Path computation is no longer helpful. Thus, this task has thus been terminated.

Improve position range-checking in the robot software. To prevent unexpected further motion in case the robot encounters unexpected resistance (including that caused by a malfunction), we had planned to modify the software so as to halt robot motion (including applying the brakes) if excessive deviation occurs between the commanded and sensed robot positions. Further motion will only be allowed re-entering teleoperation. This is so similar to the redundant encoder checking that this task will now be combined into that one.

Minimize need for surgeon & operator to interact with a computer interfaces. Keyboard-only interface on the surgeon's control station has continued to work well. It is now possible to start and even restart (without rebooting) the surgeon's control station without the need for a monitor and without having to use the mouse. We have delayed the complete elimination of the NT computer and proprietary interface hardware (Sensable technologies' I/O board and amplifier box) on the surgeon's control station because we have found Sensable's force generation capability useful for counterbalancing the surgeon's control sticks (see above). Another project here at Berkeley has developed improved replacements for the proprietary equipment mentioned above. We intend to eventually incorporate these improvements into our surgeon's control station. This will allow us to eliminate the NT computer after all, and still keep our counterbalancing feature. This approach will also leave open the possibility of eventually adding force feedback.

Next-generation watchdog circuit. The next-generation watchdog will have the ability not only to detect a failure of the computer (as with the current one) but also to detect a successful start of the robot's computer and software. This takes 2 steps out of the startup procedure. Since the last report, expertise has been developed in the programming and use of gate array logic circuits. These will allow easy, reliable implementation of sophisticated watchdog algorithms. Additional uses of gate array logic in the project may include circuitry to maintain accurate encoder positions with minimal power, such as battery backup, even when the surgical robot is not plugged in. This could allow the robot to be prepped outside the operating room, and then wheeled in and set up quickly.

Evaluate a 6 degree of freedom 3-dimensional mouse. A 6 D.O.F. haptic mouse may provide a more natural user interface for the robot than the existing haptic device which provides force feedback in only 3 of its degrees of freedom. Sensable Technologies has now developed a 6 D.O.F. mouse with full 6 D.O.F. force feedback. It may have sufficient resolution to replace the existing Phantom™ user interface device. We are considering whether this is something to which we wish to commit additional resources. This choice will be informed by what others in the field are learning about this and other 6 D.O.F. force feedback devices.

New surgeon's control sticks. In response to comments of surgeons, as well as their actions when using the robot, we have developed yet another set of control sticks

(see right frame of figure). These new control handles are designed to be held by the surgeon in the same way they already hold manual tools, such as needle drivers scissors, and hemostats. Our hope is that surgeons will be able to perform better with more familiar interface controls than they have with the current joysticks (left frame). As with the current control sticks, the mechanical configuration (particularly the relationships between rotational degrees of freedom) of the control has been matched to that of the robot. Thus, the new control sticks retain the benefit of the previous upgrade, which eliminated the need for a singularity in the kinematics calculations.

Add a disposable boot to the manipulator. We have had difficulty arriving at a satisfactory design for a disposable boot to protect the manipulator from contamination. A disposable boot to prevent contamination and fouling of the manipulator must continue to guard against contamination reliably even after experiencing the wear inherent in performing gripping tasks as well as insertion and removal through the trocar. Also, the boot must interfere with neither manipulator function nor with visualization of the manipulator or the surgery site. It must also provide for any additional functions assigned to the end effector (such as electrocautery). The robotic surgical system can be used without such a boot, but the addition of such a boot would reduce the time and effort required for achieving satisfactory cleaning and sterilization after each use. We are considering design changes to the robot wrist and end effector that will enable fitting with a satisfactory protective boot. The design of the boot has been limited by the need to pass through the trocar without breaking. This may change for beating heart surgery where it is enough to avoid stopping the heart. In this case, having the tool be minimally invasive may not be necessary. Boot development has been delayed until we have a better idea what the full requirements will be.

Add capability to adjust angle of user interface to robot. Since the last report, the system software has been modified to add the capability to adjust the angular position of the user interface device to the robot. This will allow the user interface device to be repositioned relative to the point simulating the trocar. Thus, when the camera is repositioned (to one side of the gripper, for example), the surgeon will be able to reposition the user interface device so that the correspondence between hand motions and gripper motions remains natural (that is, the front-back, left-right, and up-down translation axes still correspond).

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Zhang, Jun, Karl Hedrik Johansson, John Lygeros, Shankar Sastry. **Dynamical Systems Revisited: Hybrid Systems with Zeno Executions** Hybrid Systems: Computation and Control, Lecture Notes in Computer Science. Ed. B. Krogh and N. Lynch. Springer-Verlag, 2000

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Zweig, G. and S. Russell. **Speech Recognition with Dynamic Bayesian Networks** Proceedings AAAI-98, Madison, Wisconsin: AAAI Press, 1998

ARO MURI Scientific Personnel 1996-2001

Artemov, Sergei	Postdoctoral Researcher	Logic of Proofs
Binder, John	Graduate Student	Adaptive Probablistic Networks
Bjorner, Nikolai	Graduate Student	Verification Tools
Chua, Leon	Faculty Investigator	
Crawford, Lara	Graduate Student	Biological Control
Danning, Matt	Development Engineer	Telesurgical Workstation
Davoren, Jennifer	Graduate Student	Modal Logics
De Alfaro, Luca	Graduate Student, Postdoc	Verification Tools
Derevyanko, Dmitry	Development Engineer	Telesurgical Workstation
Freeman, Walter	Faculty Investigator	
Friedman, Nir	Postdoctoral Researcher	Learning Belief Networks
Ghosh, Sonojoy	Graduate Student	Air Traffic Control
Henzinger, Tom	Faculty Investigator	
Hoffman, Frank	Postdoctoral Researcher	Autonomous Vehicles
Hsu, Shawn	Graduate Student	Vision Control

Koller, Daphne	Faculty Investigator	
Koo, John	Graduate Student	Autonomous Vehicles
Koo, John	Graduate Student	Autonomous Vehicles
Kosecka, Jana	Postdoctoral Researcher	Vision-based Control
Kozek, Tibor	Postdoctoral Researcher	CNN UM Architecture
Lafferriere, Gerardo	Res. Engineer.	Bisimulations
Ma, Yi	Graduate Student	Visual Control
Malik, Jitendra	Faculty Investigator	
Manna, Zohar	PI, Faculty Investigator	
Mason, Cindy	Postdoctoral Researcher	Control Systems
Micheli, Mario	Graduate Student	Path Planning
Miller, Joe	Graduate Student	Modal Logics
Morrison, William	Graduate Student	Vehicle Communications
Neeley, John	Graduate Student	Neural Networks
Nerode, Anil	PI, Faculty Investigator	
Nilim, Arnab	Graduate Student	Air Traffic Management
Pappas, George	Graduate Student	Air Traffic Management
Parr, Ron	Postdoctoral Researcher	Uncertainty Analysis
Prandini, Maria	Postdoctoral Researcher	Air Traffic Management
Rajeev, Alur	Postdoctoral Researcher	Timing Verification
Russell, Stuart	Faculty Investigator	
Sastry, Shankar	PI, Faculty Investigator	
Schaffert, Shawn	Graduate Student	Vision Control
Sekhavat, Sepanta	Postdoctoral Researcher	Air Traffic Management
Sharp Cory	Graduate Student	Vision Control
Shenato, Luca	Graduate Student	Flight Models
Shi, Jianbai	Graduate Student	Grouping Problem in Vision
Shim, Hyunchul	Graduate Student	Autonomous Vehicles
Sinopoli, Bruno	Graduate Student	Autonomous Vehicles
Sipma, Henny	Graduate Student	Verification Tools
Storm, Christian	Graduate Student	Neural Networks
Tomlin, Claire	Faculty Investigator	Air Traffic Management
Tomlin, Claire	Graduate Student, Postdoc	Air Traffic Management
Tsaur, Erwin	Undergrad Student	Autonomous Vehicles
Tsaur, Erwin	Undergraduate	Autonomous Vehicles
Uribe, Tomas	Graduate Student	Verification Tools
Ustin, Jeffrey	Graduate Student	Telesurgical Workstation
Varaiya, Pravin	Faculty Investigator	
Weiss, Yair	Postdoctoral Researcher	Stereokinetic Displays
Weiss, Yair	Postdoctoral Researcher	Stereokinetic Displays
Wemhoener, Nils	Graduate Student	Path Planning
Williams, Win	Development Engineer	Telesurgical Workstation
Zadeh, Lotfi	Faculty Investigator	
Zhang, Jun	Graduate Student	Autonomous Vehicles

Degrees Awarded to ARO MURI Researchers

Bjorner, Nikolai	Ph.D.	Computer Science	Stanford Univ.	Dec 1998
Crawford, Lara	Ph.D.	Biophysical & Medical Physics	UC Berkeley	Dec 1999
Davoren, Jennifer	Ph.D.	Mathematics	Cornell Univ.	Jan 1998
De Alfaro, Luca	Ph.D	Computer Science	Stanford Univ.	Dec 1997
Ghosh Ronojoy	M.S.	Aeronautics & Astronautics	Stanford Univ.	Dec 1999
Ma, Yi	Ph.D.	EECS	UC Berkeley	June 2000
Ma, Yi	Ph.D.	EECS	UC Berkeley	Dec 1997
Pfeffer, Avi	Ph.D	Computer Science	Stanford Univ.	Dec 1999
Rodriguez, Andres	M.S.	Computer Science	Stanford Univ.	Dec 1999
Sipma, Henny	Ph.D.	Computer Science	Stanford Univ.	Dec 1998
Tong, Simon	M.S.	Computer Science	Stanford Univ.	Dec 1999
Uribe, Tomas E.	Ph.D.	Computer Science	Stanford Univ.	Dec 1998
Nils Wemhoner	M.S.	EECS	UC Berkeley	Dec 2000